

Undulators at the APS: Current State and Future Plans

Efim Gluskin on behalf of the Magnetic Devices Group

APS IDs installed as of May 2010

Period length	Number	Length (periods)	K_{eff}
33-mm (Undulator A)	25	72	2.74
33-mm	5	62	2.74
18-mm	1	198	0.46
23-mm	3	103	1.17 ^{a)}
27-mm	3	88	1.78
30-mm	2	79	2.20
30-mm	3	69	2.20
35-mm (SmCo)	1	67.5	3.08 ^{b)}
55-mm	1	43	6.57
128-mm (Circularly Polarized Und.)	1	16	$K_{x,y} < 2.8$

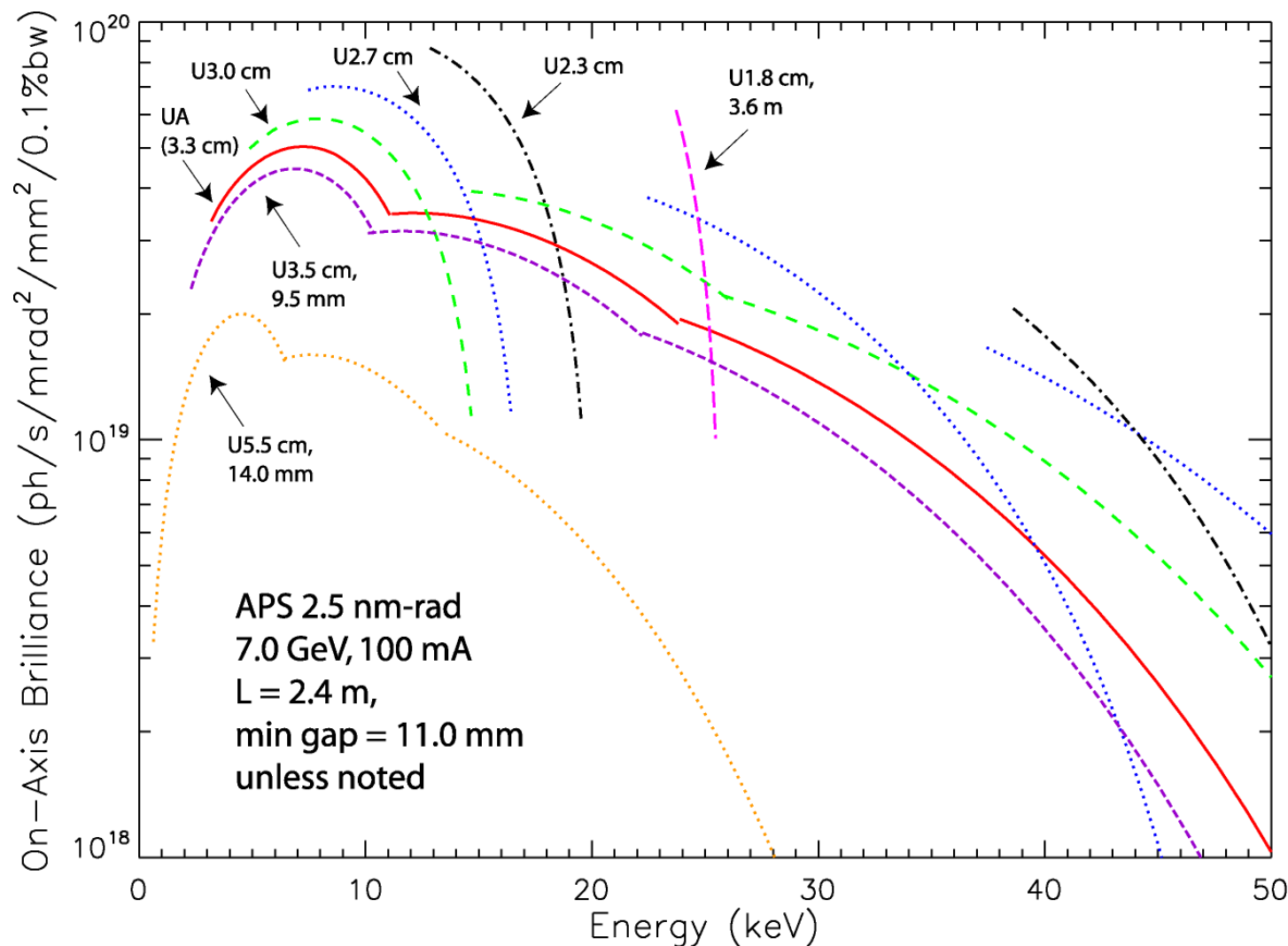
Device length includes the ends - approx. one period at each end is less than full field strength.
K value is at 10.5 mm gap unless stated otherwise. CPU is all-electromagnetic.

^{a)} at 10.6 mm gap.

^{b)} at 9.5 mm gap.

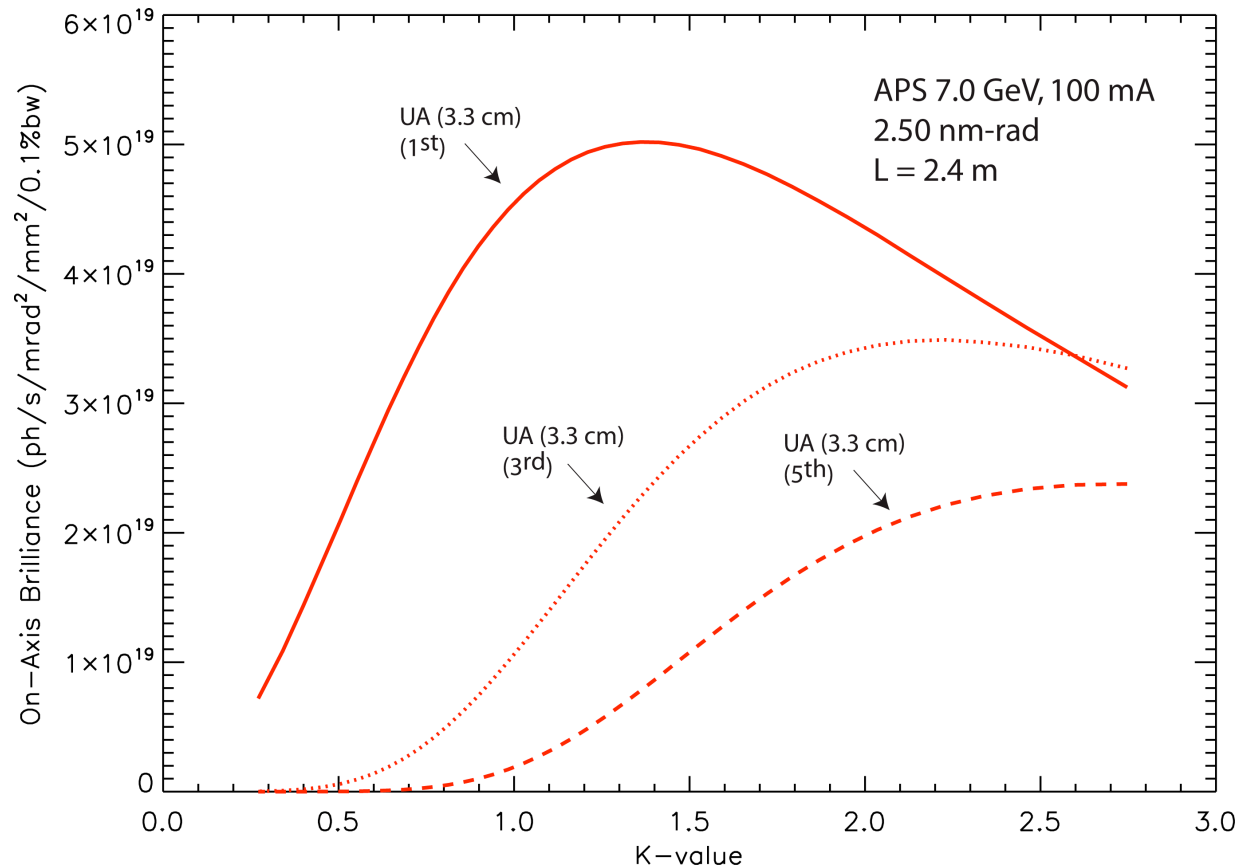
Total: 45 IDs

On-Axis Brilliance: APS Undulators



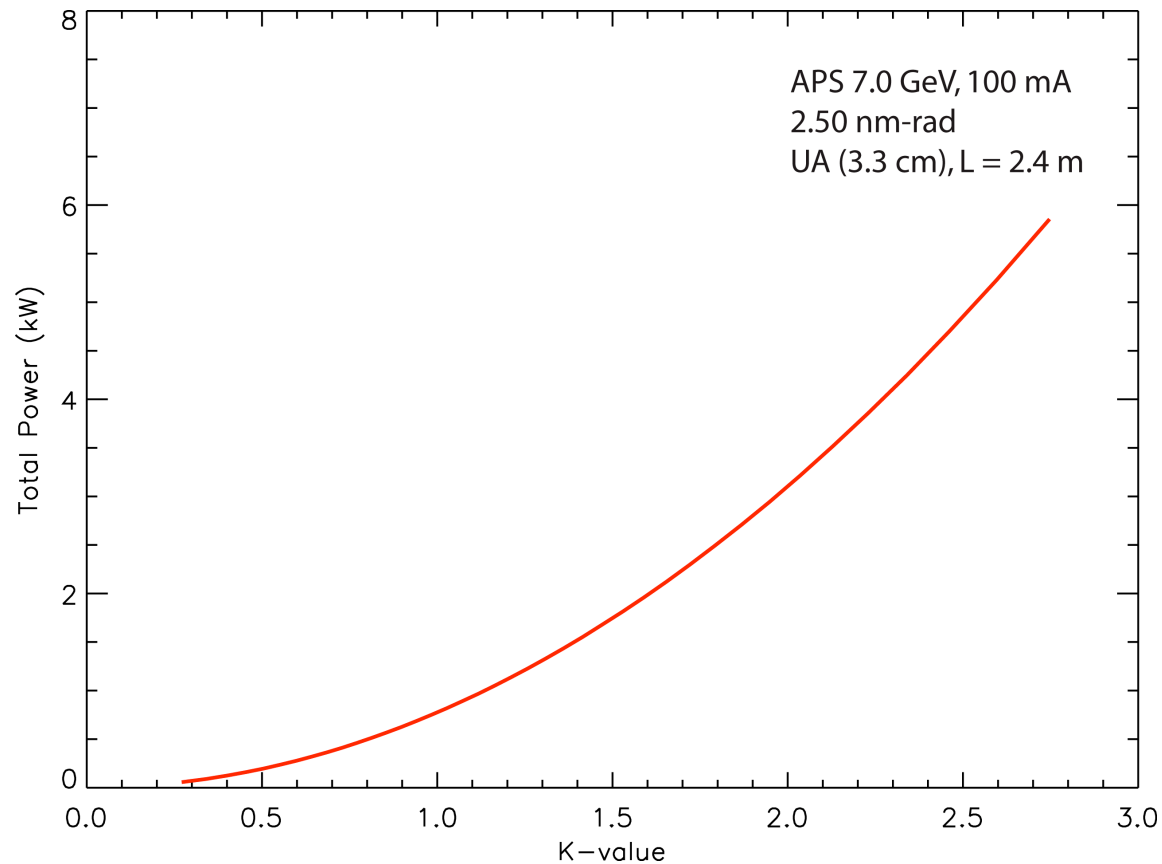
Shorter period gives higher brilliance, at higher photon energies. But tuning range is lost and gaps develop between 1st and 3rd harmonics (seen here for 2.7 and 2.3 cm period lengths) because of limited field strength.

Undulator A: On-Axis Brilliance Tuning Curves



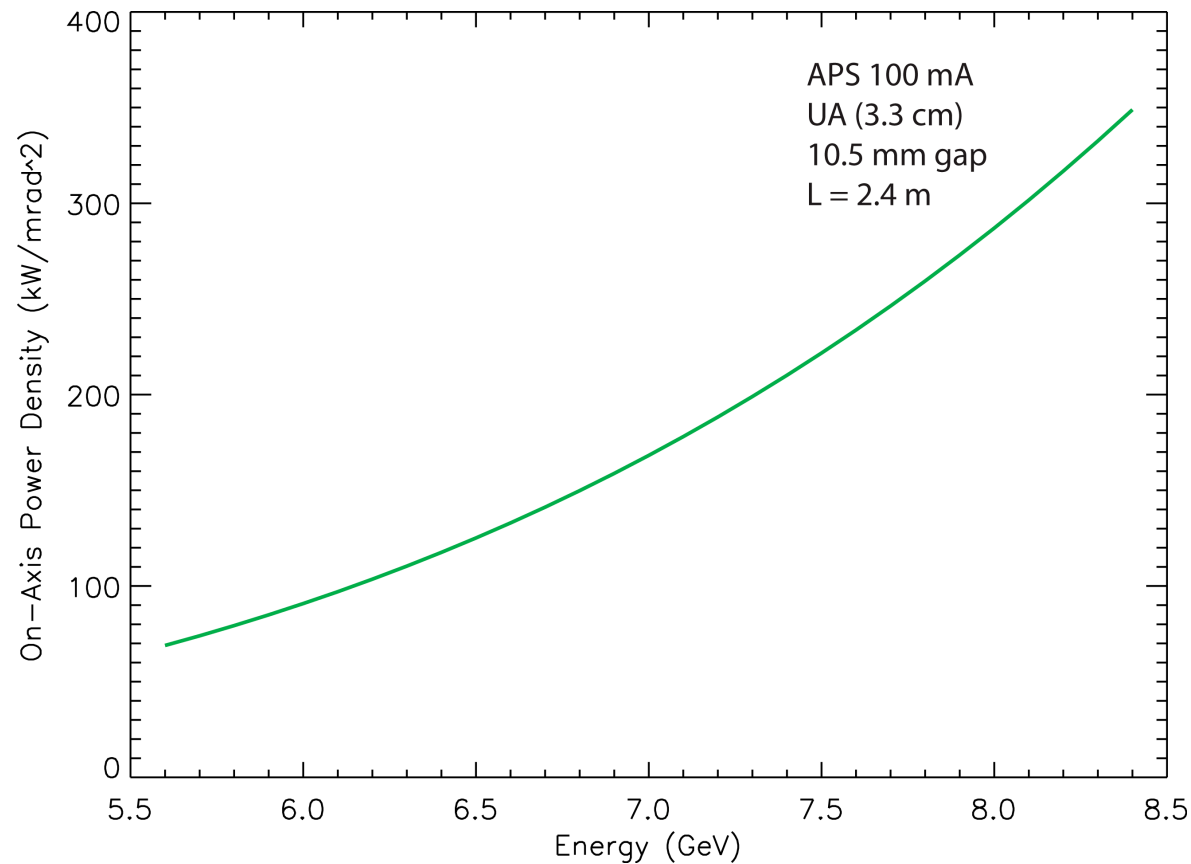
- On-axis brilliance tuning curves of the first, third, and fifth harmonics of the Undulator A for the current APS lattice for a beam current of 100 mA.

Undulator A: Total Emitted Power



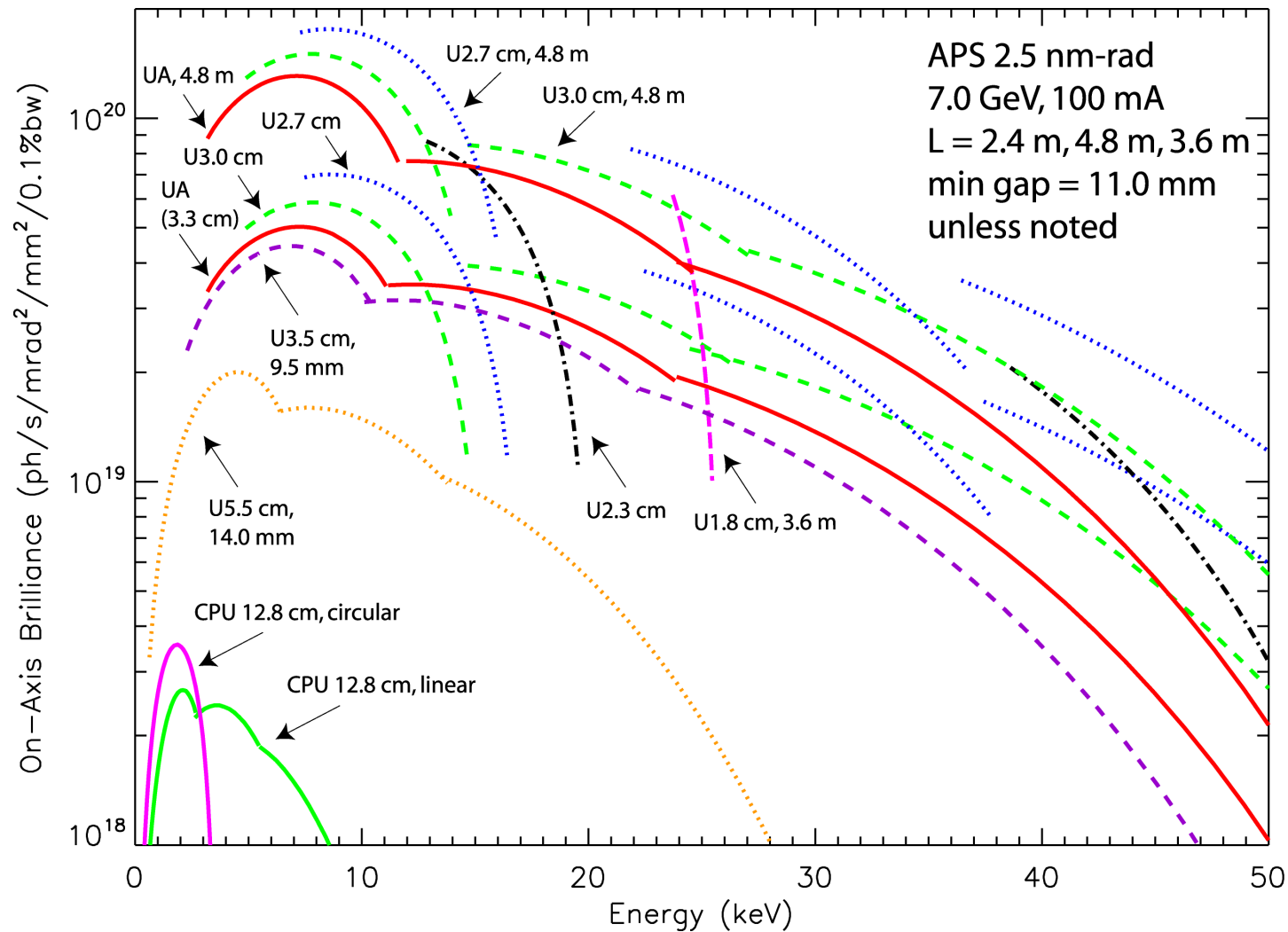
- Total emitted power of the Undulator A approaches 6 kW as the gap closes near 10.5 mm ($K \sim 2.8$) for a beam current of 100 mA.

Undulator A On-Axis Power Density Versus Beam Energy



- The on-axis power density scales with the fourth power of the beam energy ($P_{\text{dens}} \sim E^4$).

On-Axis Brilliance Tuning Curves for Existing Undulators

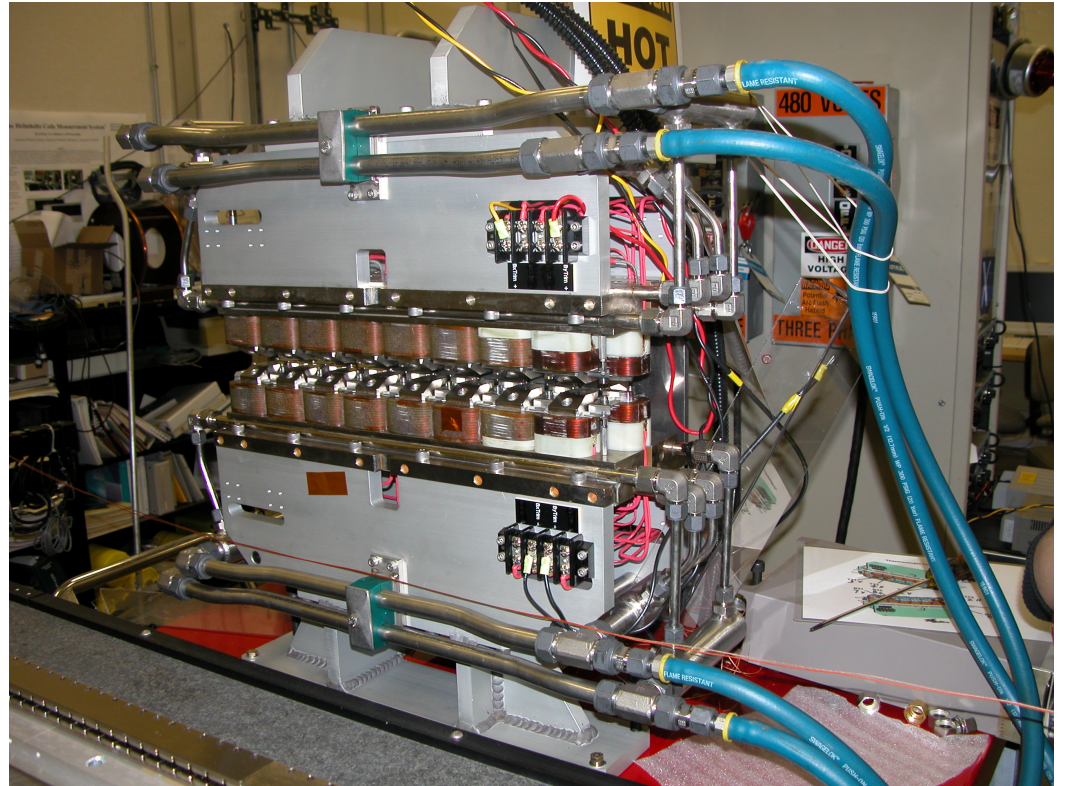
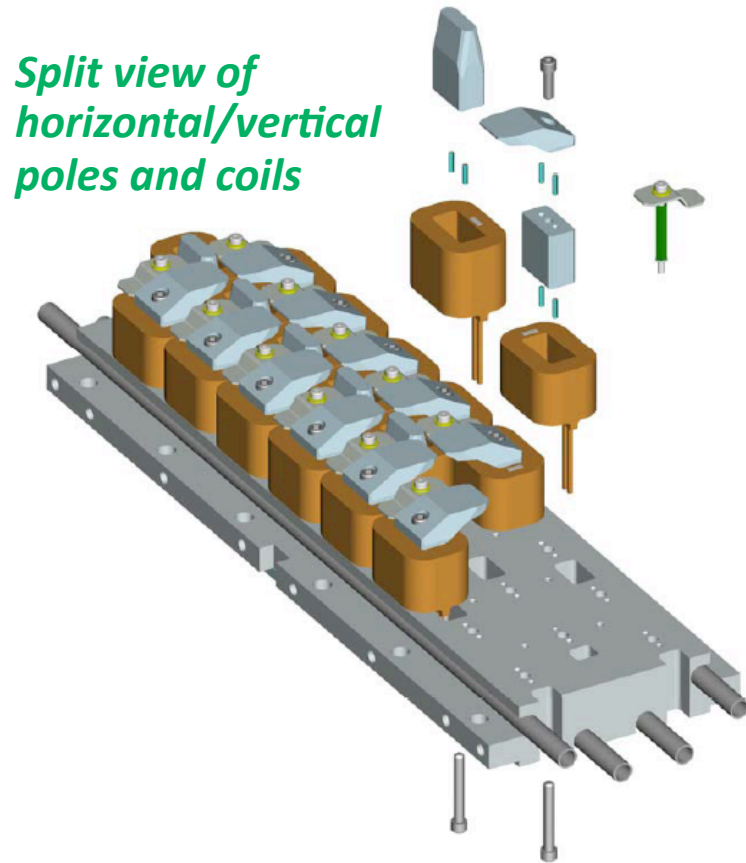


■ Beam energy 7.0 GeV, beam current 100 mA, emittance 2.5 nm-rad, and coupling 1%.

ID Magnetic Measurements and Tuning

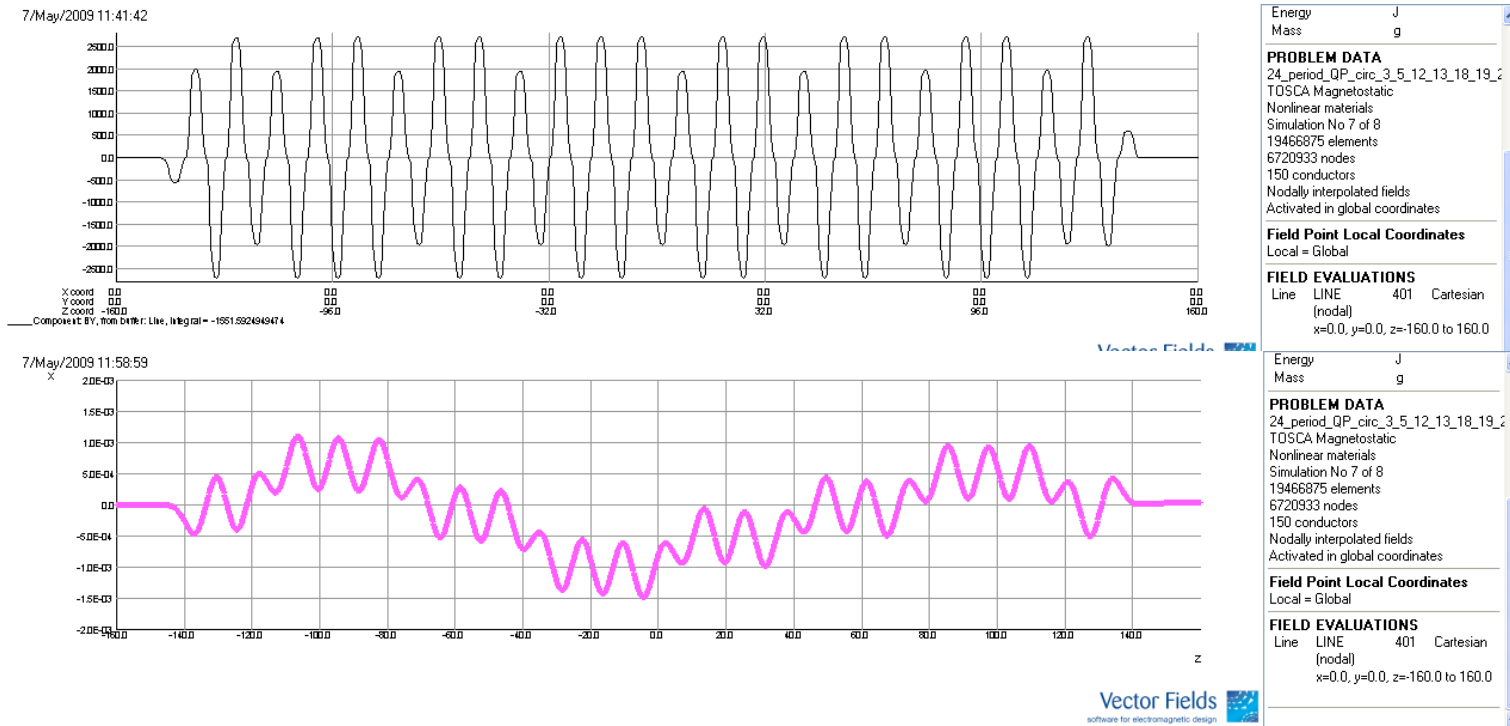
- Remarkable ID performance is due to the developed and sustained state-of-the-art Magnetic measurement facility.
- MMF has a set of unique instruments that has been constantly advanced to meet evolving requirements for APS IDs and FEL undulators.
- MMF utilizes all available and recently developed magnetic sensors.
- APS MMF has achieved record high accuracy and stability in the performance of magnetic sensors and mechanical systems.

IEX Electromagnetic Undulator: Recent Developments



- All-electromagnetic design; 12.5 cm period
- Variable polarization (linear vertical, linear horizontal, or left- or right-handed circular)
- 250 eV to 2.5 keV photon energy (~ 440 eV min. energy circular and vertical polarization)
- User-controllable quasi-periodic magnetic field for suppression of higher harmonics (magnetic field strength reduced at every 6th to 7th pole in a quasi-periodic pattern)

IEX Electromagnetic Undulator: Quasi-periodicity

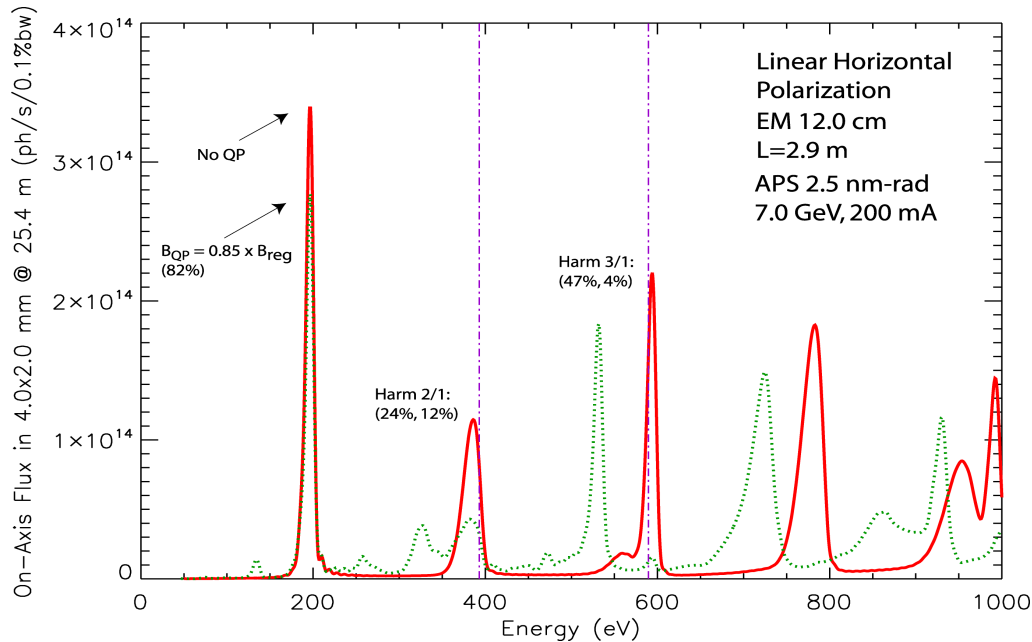


By Field

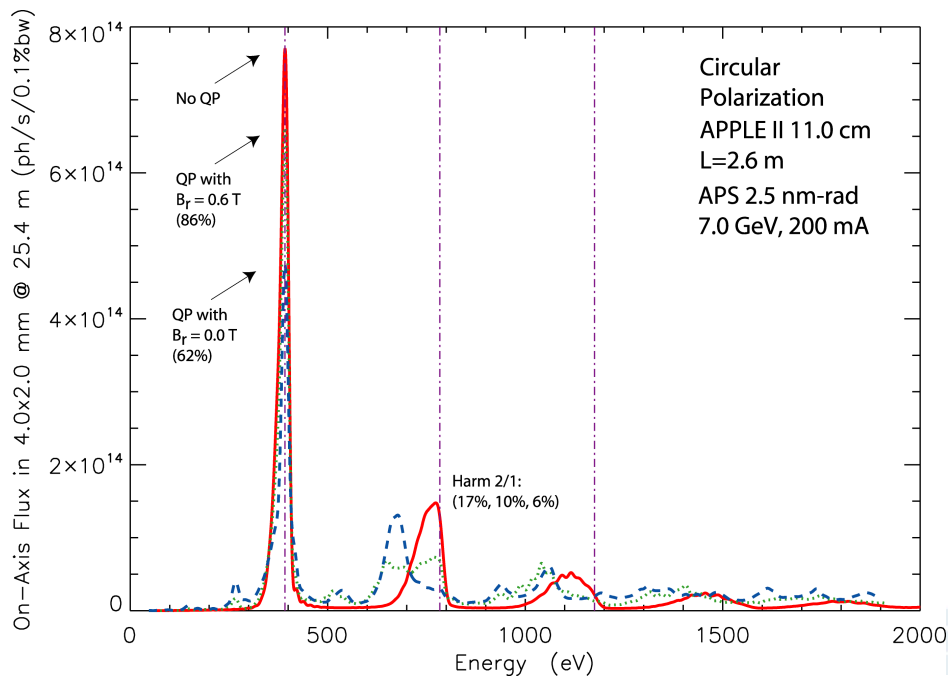
Electron
Trajectory

- The magnetic field strength of a pair of poles is reduced, every 6th or 7th pole, in a quasi-periodic pattern.

IEX Electromagnetic Undulator: Quasi-periodicity & spectrum



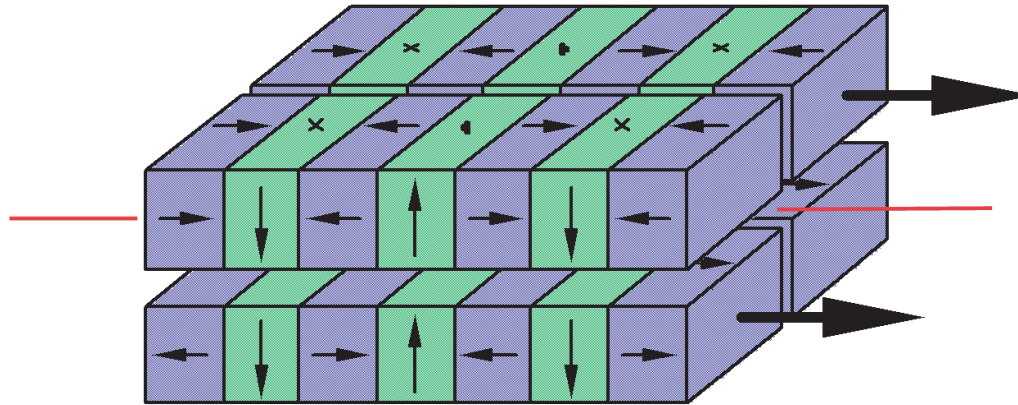
- The quasi-periodicity shifts the higher harmonics in energy so they don't make it through the monochromator.
- The biggest impact is for linear polarization, but it helps reduce higher-harmonic 'contamination' in circular mode too.
- The monochromator still sees the full power load, though.
- Quasi-periodic field reduction will be user-controllable so trade-off in photon loss vs reduction in higher-harmonic contamination can be optimized.



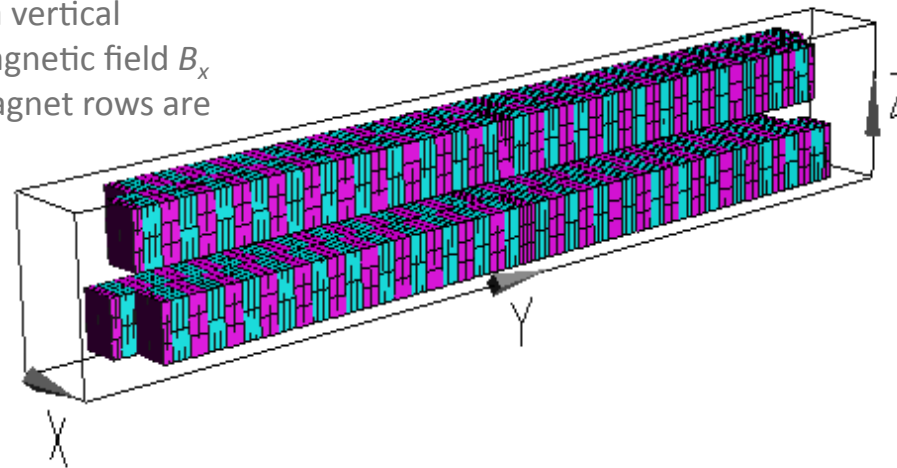
IEX Status

- The first prototype, a 4-period-long section, has been built and tested.
- During its construction, it was realized that the narrowness of the vertical field component would not be friendly to the stored beam.
- The magnetic design has been refined to reduce the impact on the stored beam to an acceptable level.
- Work is underway on a second prototype before the final 4.8-m-long device will be built.

APPLE-II Undulator Magnet Design (Schematic)



Schematic model of APPLE II device. The magnetization direction of each magnet block is indicated by the small arrows on the magnets. The large arrows indicate the two movable rows: one above the mid plane of the electron beam (red line) and one diagonally located below the mid plane. The case shown here produces only a vertical magnetic B_y in the center. The horizontal magnetic field B_x becomes non-zero on-axis when the two magnet rows are translated to the right.

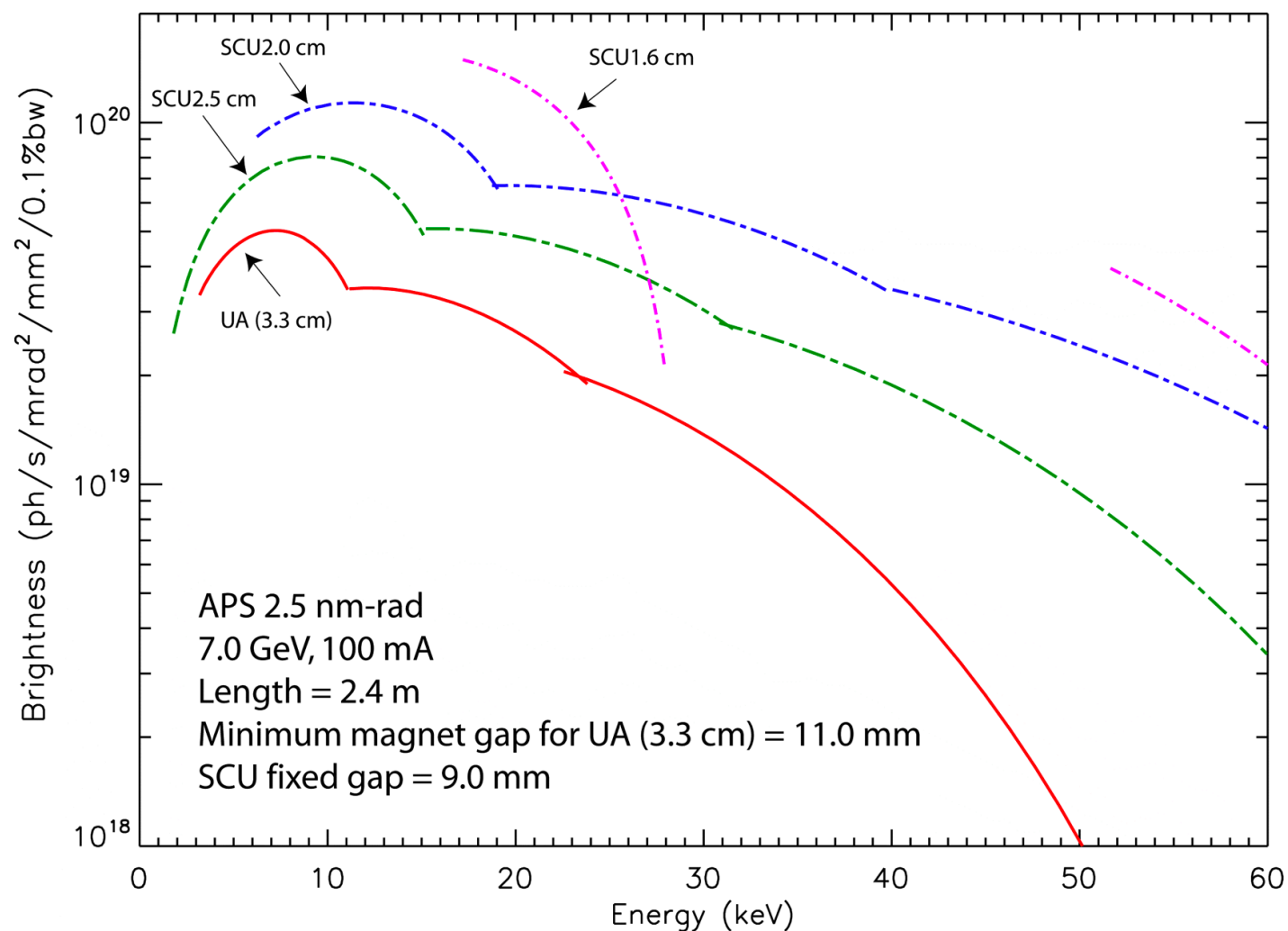


APPLE-II pros and cons

- In circular polarization mode most of the beam power goes into a ring around the beam axis, and it can be masked off.
- On axis, there is only 1st harmonic. (to within beam divergence and aperture size)
- Polarization can be changed but it is a mechanical longitudinal shift of magnet arrays so it is slow -- too slow for lock-in techniques.
- Not particularly friendly to the stored beam so will require work from accelerator physicists.
- Construction is complicated by magnetic forces between jaws.
- Phase and gap changes make magnetic tuning more complicated.

But these challenges have been met successfully at many storage rings.

Advantage of a Superconducting Undulator (SCU)



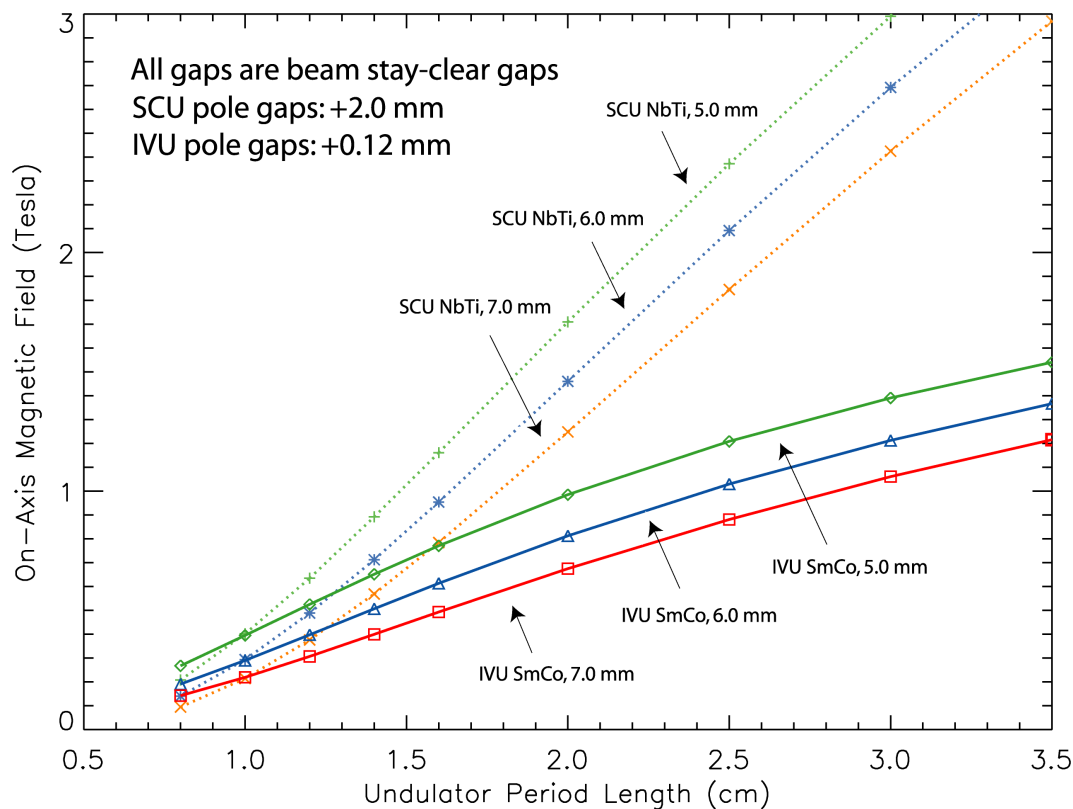
Stronger field of an SCU gives wider tuning range. The tuning range is still continuous at 2.0 cm period length.

Superconducting undulators

- APS has to take an advantage of its 7 GeV energy and strategically winning technologies in order to dominate as the high energy x-ray source.
- A superconducting undulator with existing technology allows 20-25 keV to be reached in the first harmonic. The 3rd harmonic would tune from 60-75 keV.
- 16 mm period prototype is a conservative choice.
- Prototyping started with 10-pole design and have moved on to 42-pole magnetic structures (about 1 foot long). A pair of 42-pole structures will be installed into a cryostat, presently being designed, that will keep them cold and in the necessary configuration for installation.

Increasing The Magnetic Field: In-Vacuum Undulators (IVUs) vs. Superconducting Undulators (SCUs)

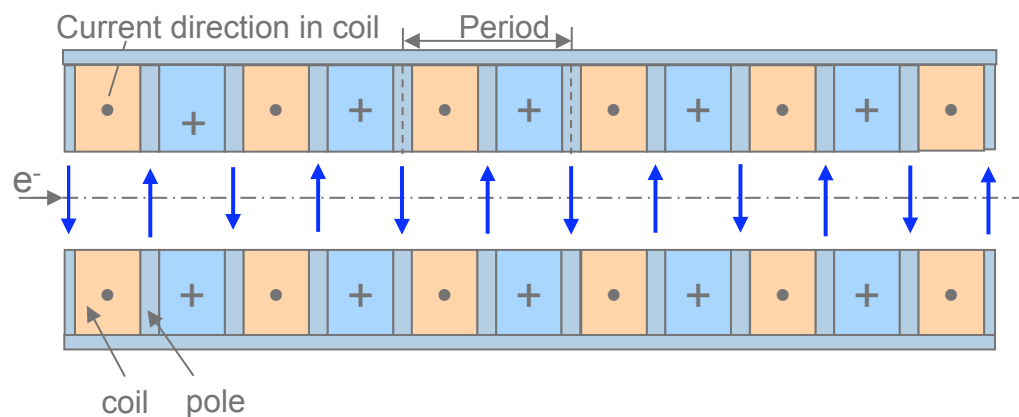
LS Note-314



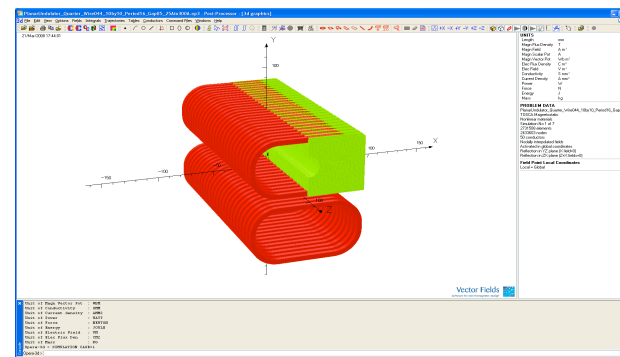
Comparison of the magnetic field in the undulator midplane for in-vacuum SmCo undulators (B_{eff}) and NbTi superconducting undulators (B_0) versus undulator period length for three beam stay-clear gaps. The actual undulator pole gaps were assumed to be 0.12 mm larger for the IVUs and 2.0 mm larger for the SCUs. Under these assumptions, about 2 mm is gained in the beam stay-clear gap for a 1.6-cm-period undulator. The effective field of the SCUs is approximately the same as the peak magnetic field B_0 .

Superconducting Planar Undulator Topology

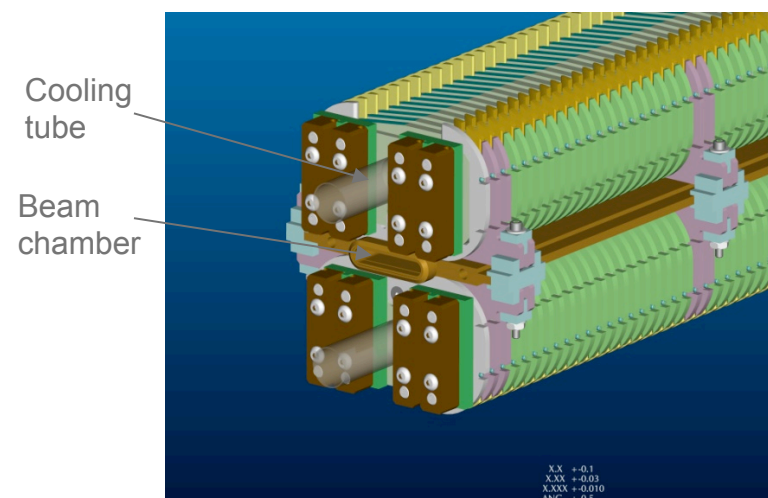
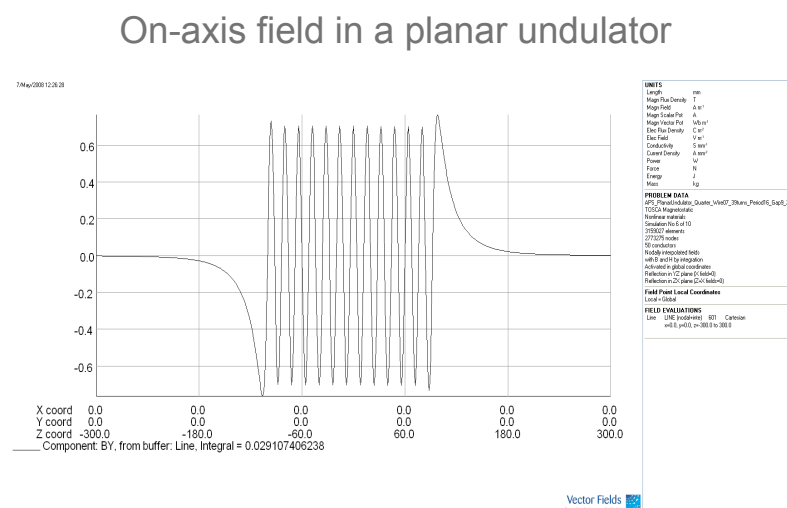
Current directions in a planar undulator



Planar undulator winding scheme

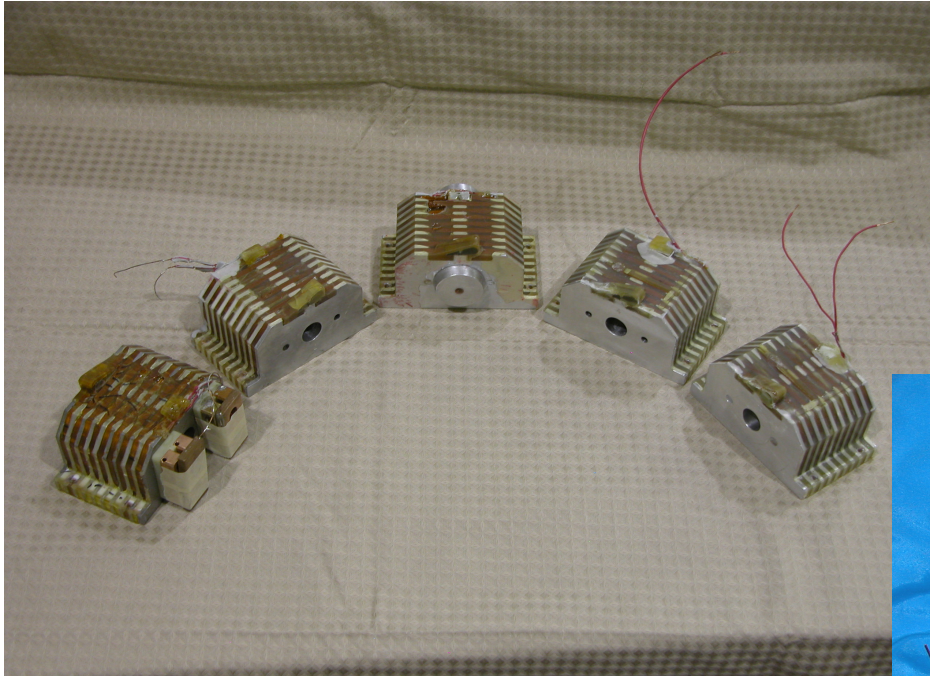


Magnetic structure layout

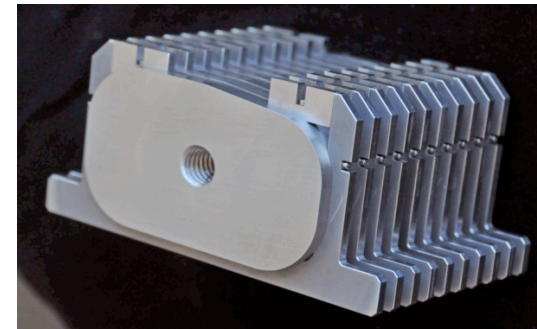


Many coils were wound as we developed winding & epoxy potting techniques

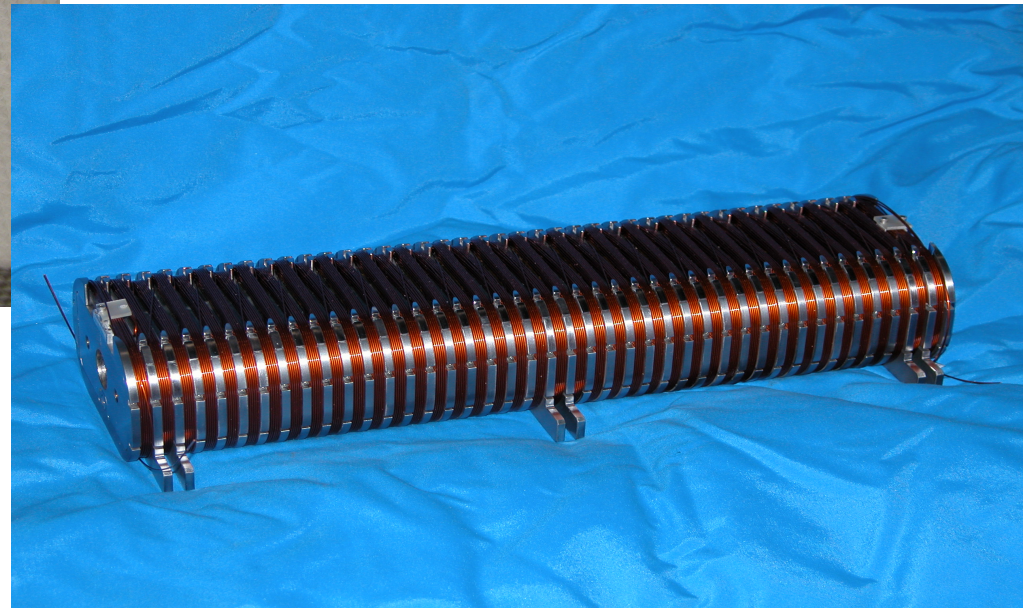
The core is assembled from separate core and pole pieces.



First five 10-pole test coils

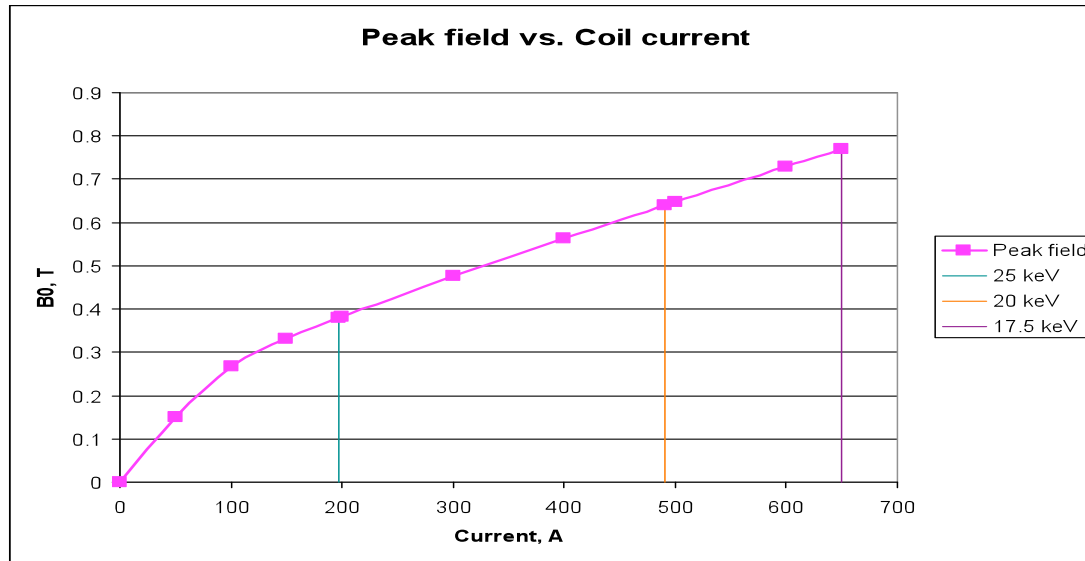


Additional windings at the ends can serve as correction coils.

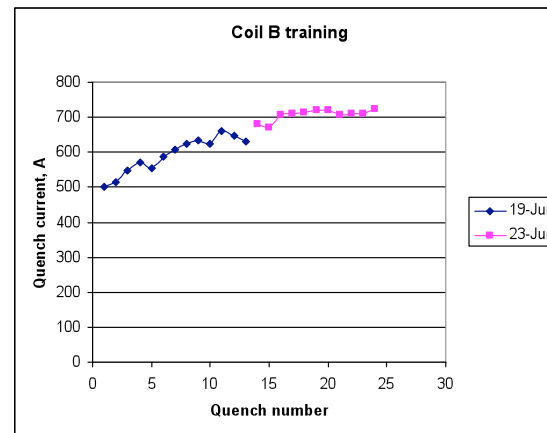
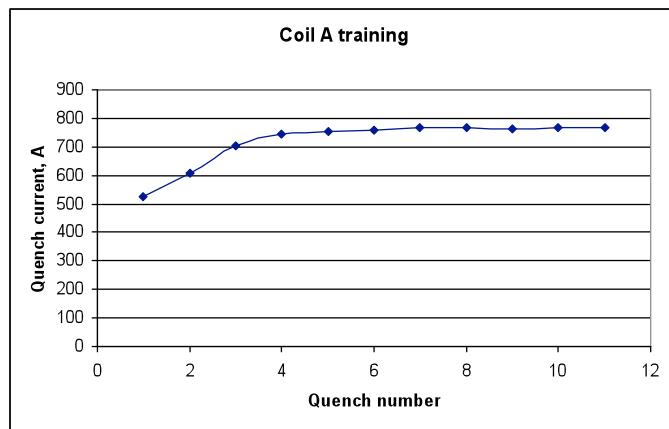
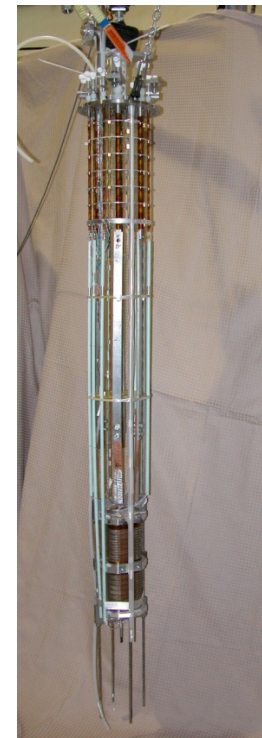


First wound 42-pole test coil

Measured coil excitation curve

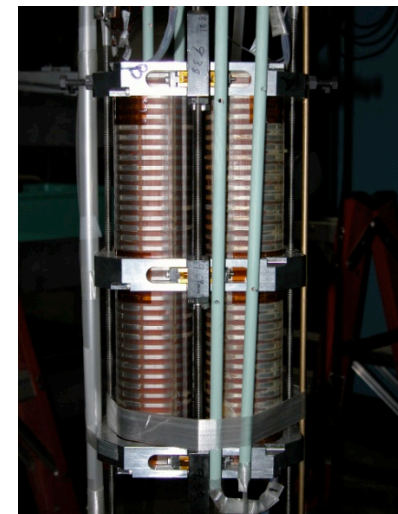


Magnetic gap: 9.5 mm
Peak field on axis:
0.38 T at 197 A
0.64 T at 491 A

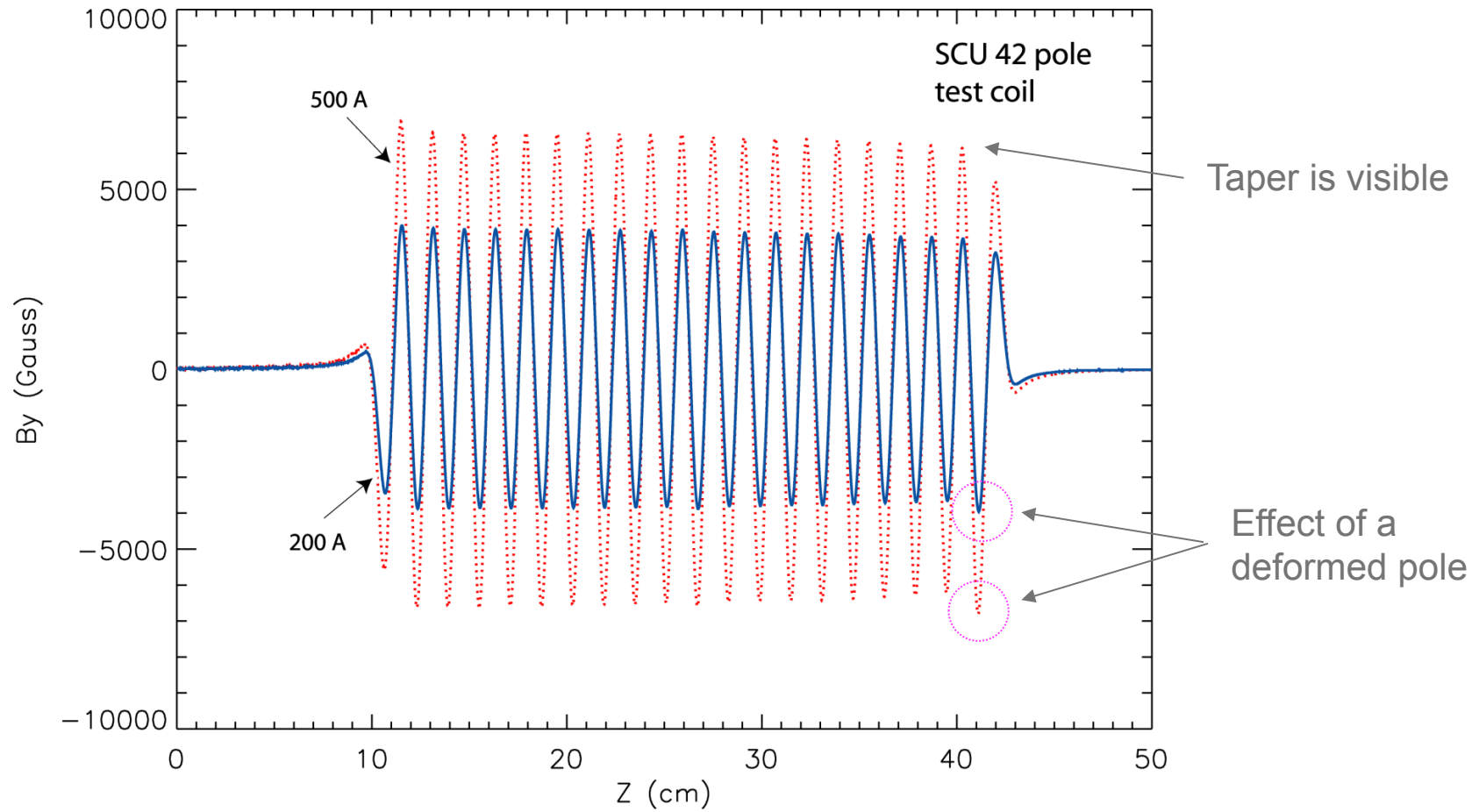


Coil A max current: 760 A, max current reached after 5 quenches

Coil B max current: 720 A, required many quenches to reach its max current



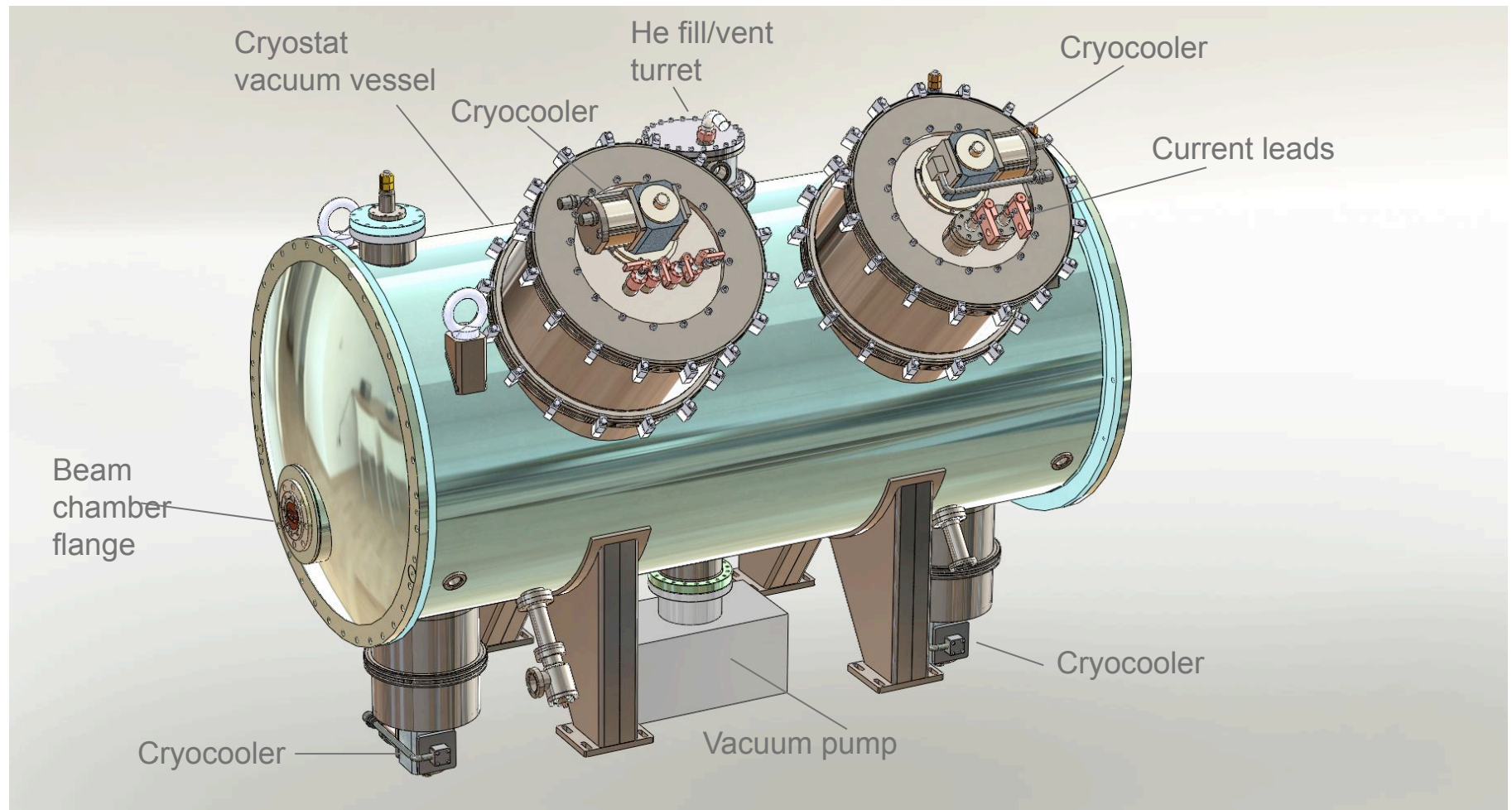
Measured magnetic field profile



- Magnetic fields were measured for currents of 200 A and 500 A at a nominal gap of 9.50 mm.
- The effective magnetic fields are 3815 Gauss (200 A) and 6482 Gauss (500 A).

- Despite the deformed pole (from a mistake during potting setup), field quality was good:
 - 3.3 deg phase error at 200 A (25 keV photon energy)
(1st, 3rd, and 5th harmonics would be 98%, 92%, and 80% of ideal)
 - 7.1 deg phase error at 500 A (20 keV photon energy)
(1st, 3rd, and 5th harmonics would be 95%, 75%, and 50% of ideal)

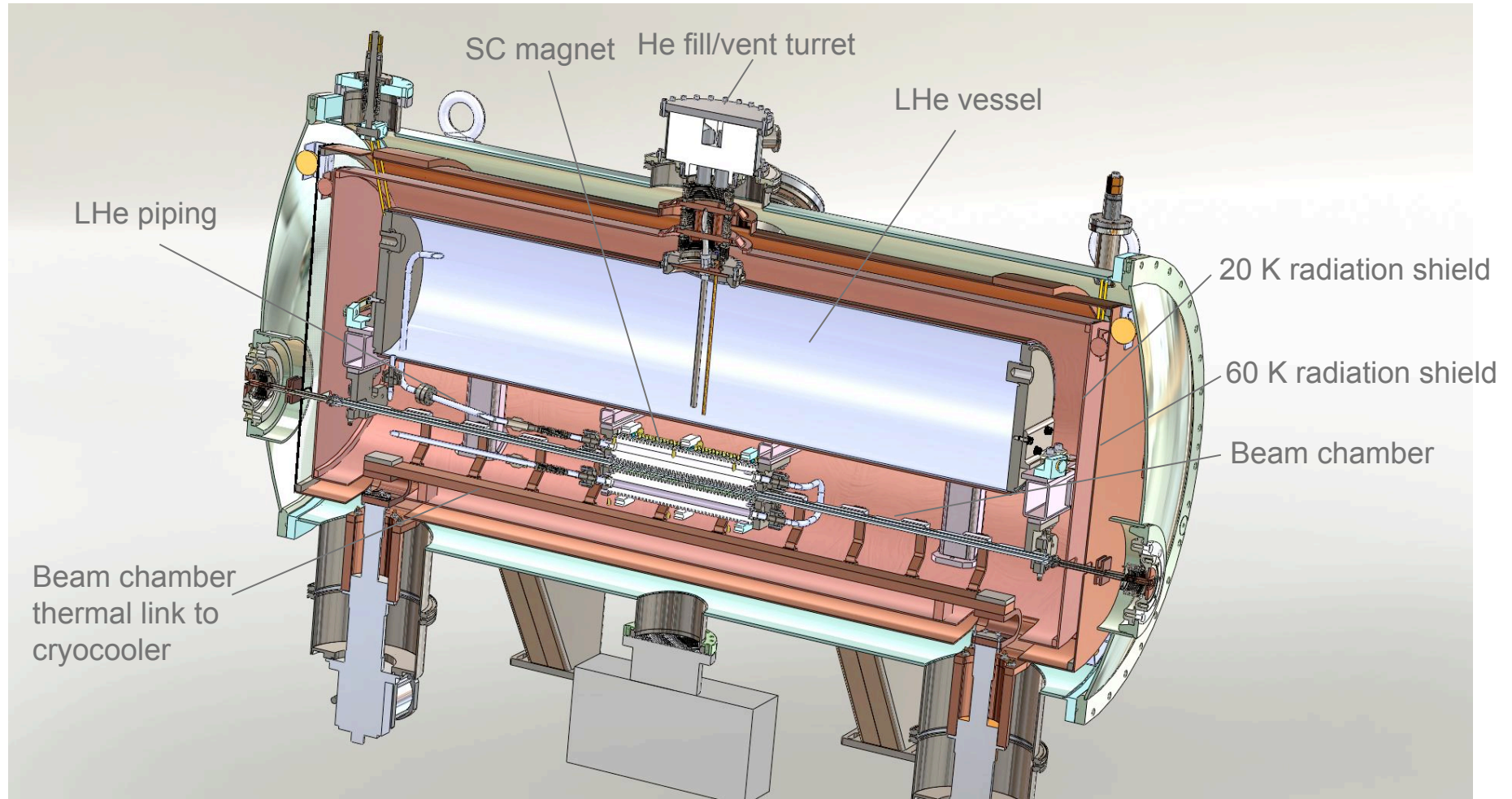
Cryostat



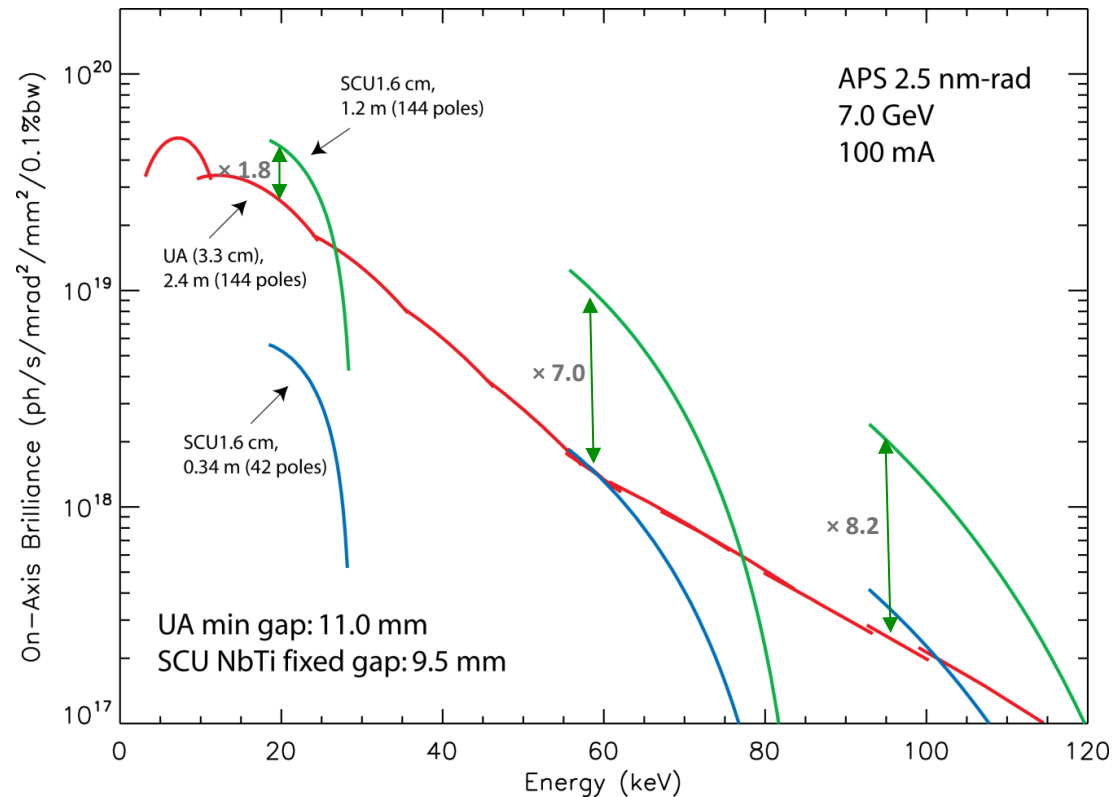
Cryostat is 2.06 m long, so will fit in half of the straight section

Cryostat structure

Cryostat contains cold mass with support structure, radiation shields, cryocoolers, and current lead assemblies.

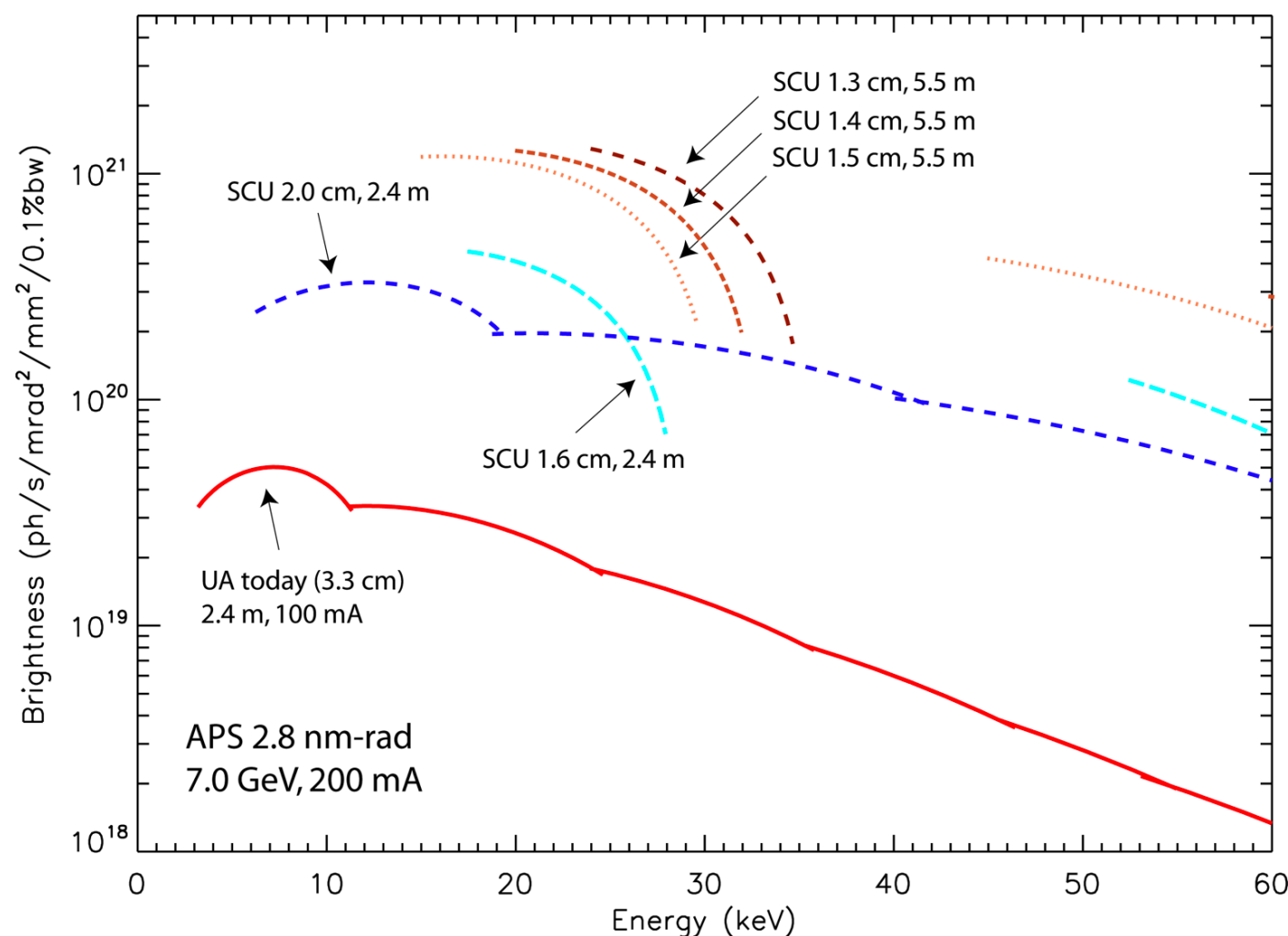


Expected performance of SCU0 and SCU1



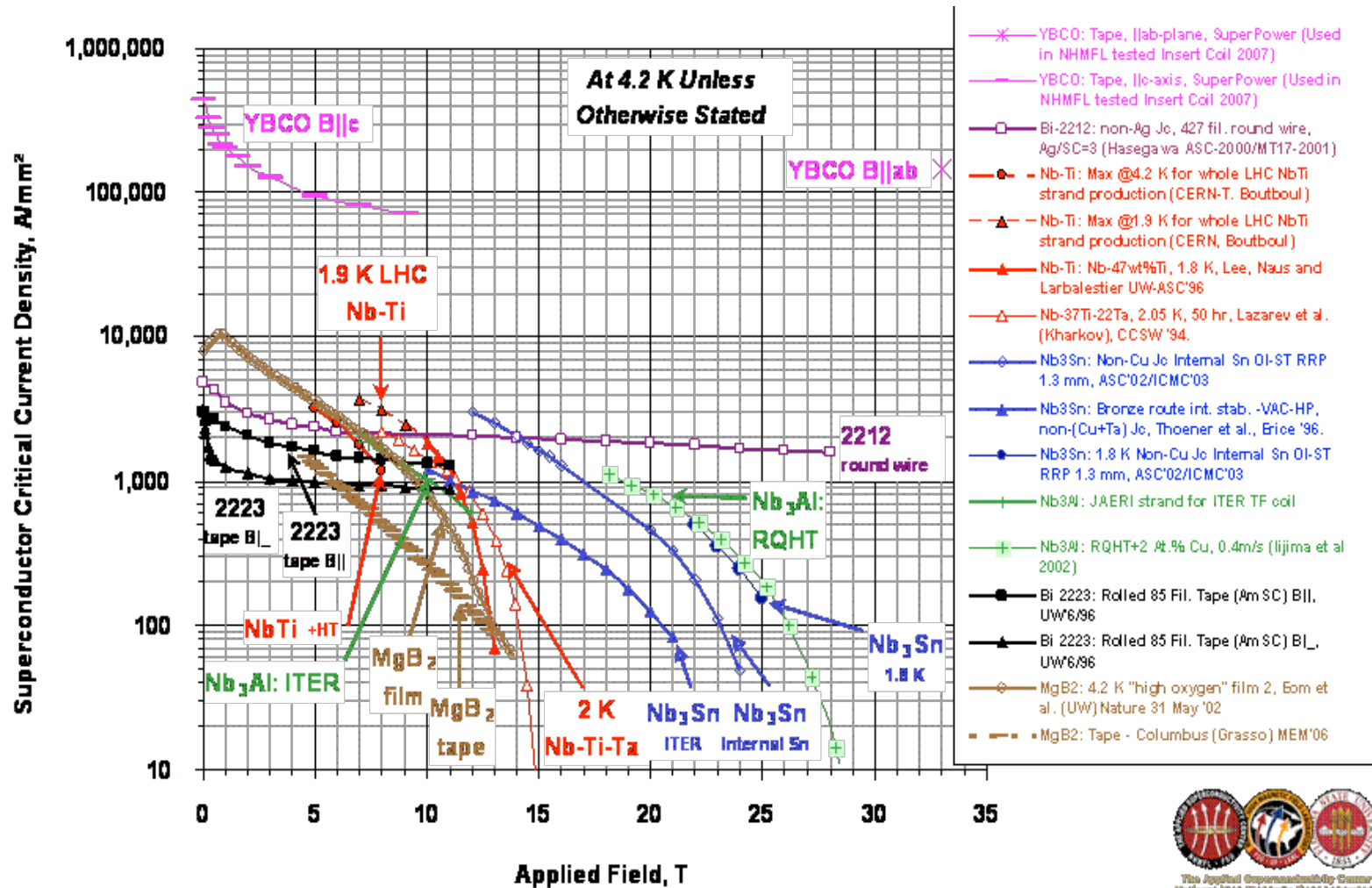
- Tuning curves for odd harmonics for two planar 1.6-cm-period NbTi superconducting undulators (42 poles, 0.34 m long and 144 poles, 1.2 m long) versus the planar NdFeB permanent magnet hybrid undulator A (144 poles, 3.3 cm period and 2.4 m long). Reductions due to magnetic field error were applied the same to all undulators (estimated from one measured undulator A at the APS). The tuning curve ranges were conservatively estimated for the SCUs.
- The minimum energies are 3.2 keV for the UA and 18.6 keV for the SCUs.
- The short 42-pole 1.6-cm-period SCU surpasses undulator A at ~ 60 keV and ~ 95 keV. The 144-pole SCU brilliance exceeds that of undulator A by factors of 1.8 at 20 keV, 7.0 at 60 keV, and 8.2 at 95 keV.

More distant future, after the APS upgrade and with longer SCUs



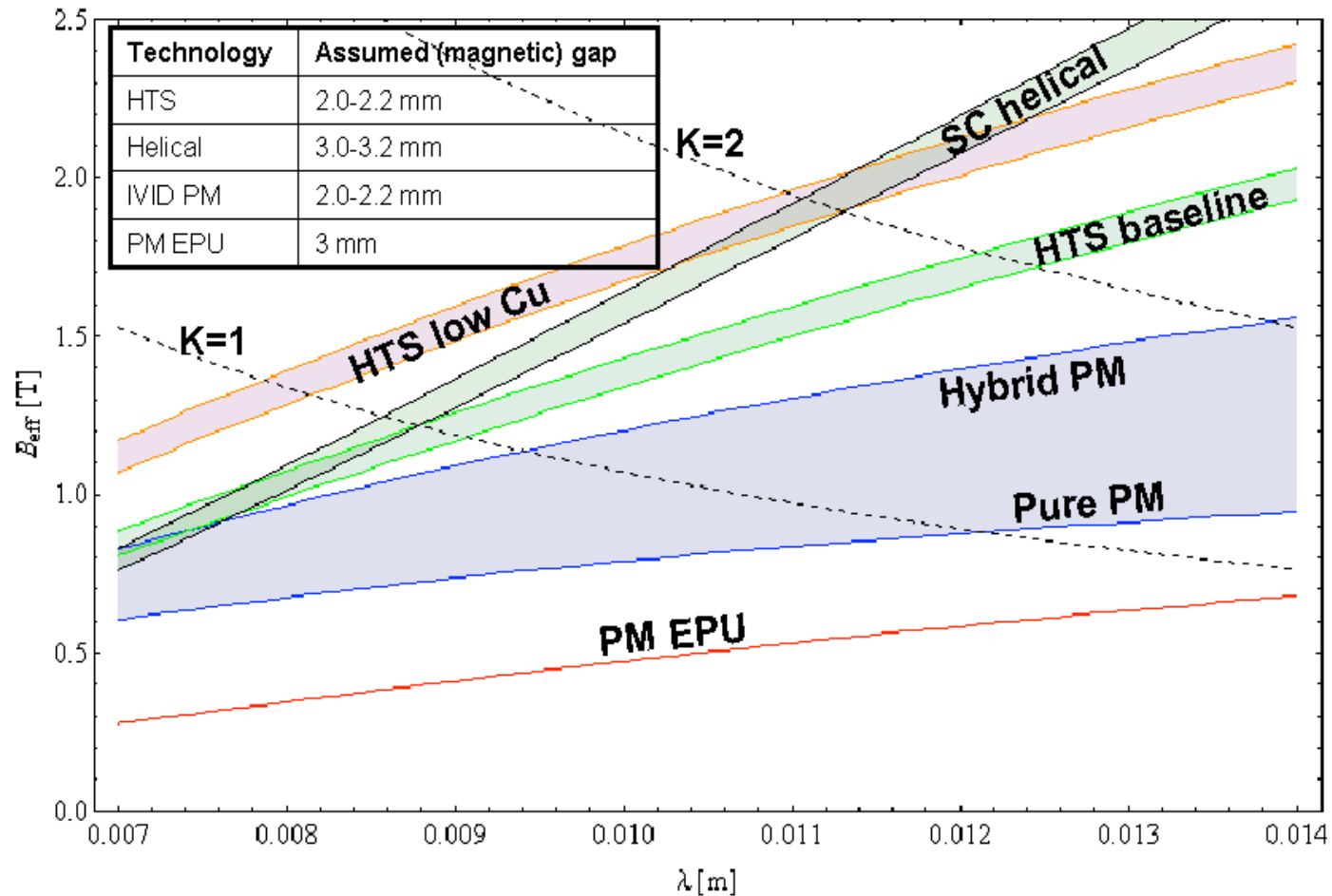
Brightness tuning curves for superconducting undulators installed on APS-U (with 200-mA beam current). A tuning curve for Undulator A on today's APS (with 100 mA) is indicated for comparison. The SCU 1.6 cm is more than an order of magnitude brighter than the Undulator A between 20 and 25 keV.

Critical current for different superconductors



Courtesy of S.Prestemon, LBL

Comparison of short-period undulator technologies



Courtesy of S.Prestemon, R.Schlueter, et.al., LBL